

Cooling of strange stars in the color-flavor locked phase with a rotating crust

Yu Yunwei, Zheng Xiaoping¹

The institute of astrophysics, Huazhong normal university, Wuhan 430079, Hubei, P.R.China.

ABSTRACT

The presence of the color-flavor locked (CFL) phase strongly suppresses the neutrino emission processes and the quark specific heat. As a result the cooling of the strange stars in the CFL phase is dominated by deconfinement heating and surface emission. The temperature of these stars with strong magnetic field ($B \geq 10^{10} G$) rise significantly during the first several ten or hundred years, which may be an effective signature of strange stars as implicated by pulsar 0540-69. Furthermore a limit line is predicted, which means compact stars have an upper limit temperature at any moment. We still may search for the candidates for strange stars in the CFL phase along the limit line.

Subject headings: stars: evolution, stars: neutron, pulsars: general

1. Introduction

Strange quark matter (SQM) which is made up of roughly equal numbers of up, down and strange quarks, is postulated to be absolutely stable, may be more stable than atomic nuclei (specially iron). If this hypothesis is correct, strange quark star (strange star, SS) may exist.

Theoretical and observational researches on SSs might provide a signature to distinguish SSs from neutron stars, consequently to test what is the true ground state of hadron. One of the clues is based on their thermal evolution behaviors. At the first time, it is generally accepted that the surface temperature of SSs should be lower than neutron stars at the same age due to the quark direct Urca (QDU) process (Alcock et al. 1988, Pizzochero 1991, Page 1992, Schaab et al. 1996). However, since the electron fraction could be small or even vanish, the QDU process may be switched off. And the cooling of SSs dominated by the quark modified Urca (QMU) and the quark bremsstrahlung (QB) processes could be slower than neutron stars with standard cooling (Schaab et al. 1997a, b).

Subsequently the effect of color superconductivity on the cooling of SSs is investigated (Blaschke et al. 2000). It is shown that stars in the color flavor locked (CFL) phase cool down extremely rapid. The cooling curves have a exceedingly departure from the observed data. The stars became so cold that they can't be observed in the X-ray band after several hundred years from their birth.

However, it is also indicated that SSs, with the spin down due to magnetic dipole radiation, could be heated. The core density of the stars increase with the decrease of rotate velocity, which induce the so-called chemical heating (Reisenegger 1995, Cheng et al. 1996). On the other hand it is referred that SSs should have a tiny crust of normal nuclear matter. The spin down of SSs leads to the nuclear matter, falling into

¹Email: zhxp@phy.ccnu.edu.cn

the quark core continuously, converts into quark matter and release binding energy to heat the stars. This heating mechanism is called deconfinement heating (DH), whose effect is more important than chemical heating (Yuan et al. 1999).

It should be noted that for SSs with the effect of DH, it may be not a certainty that SSs cool down rapid even in the CFL phase. Thus it is necessary to restudy the cooling behaviors of SSs in the CFL phase (CSSs), which is beneficial to clarify whether CSSs could be observed in the X-ray band or not. In this paper we consider the model of stars with a thin crust. We show the cooling history of stars due to the DH effect and the presence of the CFL phase, which may characterize significantly astrophysical relevance. Especially our results indicate the existence of a possible limit line of stars' cooling. Hence at a certain age there may exist an upper limit temperature which only CSSs can reach. The arrangement in this paper follows as: the emissivities and specific heat, the effects of color superconductivity and deconfinement heating are discussed in section 2, 3, 4 respectively. In section 5 we evaluate the cooling curves for many cases and compare them. In final section a summary and conclusion are given.

2. Neutrino emissivities and specific heat

The emissivity associated with the QDU process $d \rightarrow ue\bar{\nu}$ and $ue \rightarrow d\nu$ of quarks without color superconductivity (Iwamoto 1982) is

$$\epsilon^{(D)} \simeq 8.8 \times 10^{26} \alpha_c \left(\frac{\rho_b}{\rho_0} \right) Y_e^{1/3} T_9^6 \text{ erg cm}^{-3} \text{ sec}^{-1}, \quad (1)$$

where α_c is the strong coupling constant, ρ_b is baryon density and $\rho_0 = 0.17 \text{ fm}^{-3}$ is the nuclear saturation density, and T_9 is the temperature in units of 10^9 K . The electron fraction $Y_e = \rho_e / \rho_b$ may vanished at a certain baryon density, α_c and s-quark mass m_s . We did not consider the contribution of the QDU process involving strange quark since it is suppressed compared to the corresponding ud -reactions (Duncan et al., 1983) by an factor $\sin\theta_C \sim 10^{-3}$, where θ_C is the Cabibbo angle. Evidently $\epsilon_d^{(D)}$ is sensitively dependent on the electron fraction Y_e from (1). When the QDU process is switched off due to small electron fraction, the contribution to the emissivities by the QMU process $dq \rightarrow uqe\bar{\nu}$ and the QB processes $q_1 q_2 \rightarrow q_1 q_2 \nu \bar{\nu}$ are dominative. These emissivities were also estimated as (Iwamoto 1982)

$$\epsilon^{(M)} \simeq 2.83 \times 10^{19} \alpha_c^2 \left(\frac{\rho_b}{\rho_0} \right) T_9^8 \text{ erg cm}^{-3} \text{ sec}^{-1}, \quad (2)$$

$$\epsilon^{(B)} \simeq 2.98 \times 10^{19} \left(\frac{\rho_b}{\rho_0} \right) T_9^8 \text{ erg cm}^{-3} \text{ sec}^{-1}. \quad (3)$$

In accordance with the calculation of Iwamoto (1982) and Blaschke et al. (2000) we have the specific heat of the quarks and electron

$$c_q \simeq 2.5 \times 10^{20} \left(\frac{\rho_b}{\rho_0} \right)^{2/3} T_9 \text{ erg cm}^{-3} \text{ K}^{-1}, \quad (4)$$

$$c_e \simeq 0.6 \times 10^{20} \left(\frac{Y_e \rho_b}{\rho_0} \right)^{2/3} T_9 \text{ erg cm}^{-3} \text{ K}^{-1}. \quad (5)$$

Since the mass of crust is very small $M \leq 10^{-5} M_\odot$ comparing with the total mass of the star (Gudmundsson et al. 1983), its contribution to the emissivities can be neglected. And specific heat of the crust is also very small (Lattimer et al. 1994). Here we have also ignored the neutrino emissivity and the specific heat

due to the photon-gluon excitation. Because this excitation is only important for the temperature higher than 70MeV (Blaschke et al. 2000) which is much higher than the typical temperature in our calculation.

3. Color superconductivity

It is widely accepted the color-flavor locked (CFL) phase is the real ground state of quantized chromodynamics at asymptotically large densities. At a certain range of the quark chemical potential the quark-quark interaction is attractive, driving the pairing with a large pairing gap (Alford et al. 1998, 1999, Rapp et al. 1998). In Refs. (Alford et al. 1999, 2003) the gap obtained from the solution of the gap equation. We take gap values from 0.1MeV to 100MeV in the calculation below. In presence of CFL phase, the QDU process is suppressed by $\exp(-\Delta/T)$ and the QMU & QB processes are suppressed by $\exp(-2\Delta/T)$ of all quarks (Blaschke et al. 2000). The specific heats of the paired quarks are also changed, we apply the formula (Blaschke et al. 2000)

$$c_{sq} = 3.2c_q \left(\frac{T_c}{T} \right) \left[2.5 - 1.7 \left(\frac{T}{T_c} \right) + 3.6 \left(\frac{T}{T_c} \right)^2 \right] \exp \left(-\frac{\Delta}{T} \right), \quad (6)$$

where critical temperature $T_c \simeq 0.4\Delta$. Since the cooling behavior of strange stars in the 2SC phase is not very different from the case without color superconductivity (Blaschke et al. 2000), we do not consider here.

4. Deconfinement heating

Because strange quark mass is greater than the up and down quarks, a normal strange star (NSS) will form a strong electric field on SQM surface due to electrons for charge neutrality (Alcock et al. 1986). The electric field can suspend a nuclear crust out of contact with SQM, but any material that contains a component of free neutron (not bound in nuclei) will not be stable. Consequently the density at the base of the crust is strictly limited by neutron drip. Commonly it is accepted that bulk SQM in the CFL phase is electric neutrality in the absence of electron due to equal quark Fermi momenta. However the surface tension effect of the bulk SQM is highly flavor dependent (Madsen 2001), so Usov (2004) showed that a Coulomb barrier with electrostatic potential of $3.6 \times 10^7 \text{V}$ is still present at the SQM surface in the CFL phase. Thus there may also exist a nuclear matter crust for CSS. The calculation in general relativity of a rotating strange star show that the mass of the crust is reduced due to the decrease of the rotate velocity Ω from the Kepler angular velocity to zero (Glendenning et al. 1992). The crust mass as a function of Ω is fitted by the analytic expression (Yuan et al. 1999)

$$M_c(\Omega) - M_c(0) = 10^{-5} M_\odot \left[0.238 \left(\frac{\Omega}{\Omega_K} \right) + 0.389 \left(\frac{\Omega}{\Omega_K} \right)^2 + 1.15 \left(\frac{\Omega}{\Omega_K} \right)^3 \right]. \quad (7)$$

With the decrease of Ω , the surplus matter in the crust falls into the quark core in the form of neutrons which are absorbed by quark bag in an exothermic reaction, i.e., $n \rightarrow u + 2d$. During this process, the energy produced per baryon in the core is given by (Yuan et al. 1999)

$$\frac{dE}{dt} = -q_n \frac{1}{M} \frac{dM_c(\Omega)}{d\Omega} \frac{d\Omega}{dt}, \quad (8)$$

where q_n , the heat release per absorbed neutron, is expected to be in the range $q_n \sim 10 - 30 \text{MeV}$ (Haensel et al. 1991), and M is the total mass of the star. We assume the spin decrease is due to the magnetic dipole

radiation, then

$$\frac{d\Omega}{dt} = -\frac{2}{3Ic^3}\mu^2\Omega^3\sin^2\alpha, \quad (9)$$

where I is the stellar moment of inertia, $\mu = \frac{1}{2}BR^3$ is the magnetic dipole moment and α is the inclination angle between magnetic and rotational axes.

5. Cooling curves

The thermal evolution of the stars is determined by the equation:

$$C\frac{dT}{dt} = -L_\nu - L_\gamma + H, \quad (10)$$

where C is the total specific heat, L_ν is the total neutrino emissivity, H is the heating power, and L_γ is surface thermal luminosity which is given by

$$L_\gamma = 4\pi R^2\sigma T_s^4, \quad (11)$$

where σ is the Stefan-Boltzmann constant and T_s is the surface temperature. The internal structure of SSs can be regarded as temperature independent (Glen et al., 1980), and we apply the relationship of internal temperature and surface temperature that is calculated by Potekhin et al. (1997).

In our calculation, we take $M = 1.4M_\odot$, $R = 10\text{km}$, $q_n = 20\text{MeV}$, and $m_s = 200\text{MeV}$, and choose the initial temperature $T_0 = 10^9\text{K}$, the initial period $P_0 = 0.78\text{ms}$, and the magnetic tilt angle is 45° . Different groups of data points are taken from Table 3 of Ref. (Schaab et al. 1999) where the notations are explained.

Firstly we plot the cooling curves of NSSs for $B = 10^{12}\text{G}$ (curve a), 10^{11}G (curve b), 10^{10}G (curve c), 10^9G (curve d), 10^8G (curve e) in fig.1. The QDU process with $Y_e = 10^{-5}$ lead to rapid cooling (solid lines) disagree with the data. And the QMU & QB processes, when QDU process is switched off for too small electron fraction, have much slow cooling (dotted lines) relative to the data.

Fig.2 shows the cooling curves of CSSs for the same cases in Fig.1. The curves of CSSs with strong magnetic field ($B \geq 10^{10}\text{G}$) have a sudden increase of temperature, which maintain steady for the first several ten or hundred years. With a certain strong magnetic field, the increase of the temperature just explains the pulsar 0540-69 leaping out of the clusterized pulsar data. This may be an implication of the existence of CSSs if more events such as pulsar 0540-69 are observed. For the case of weak magnetic field ($B \leq 10^{10}\text{G}$), the protrusions in the cooling curves disappear and the curves gently slope through the densely populated region by pulsar data. The temperature of these stars is still high even at the old ages ($\geq 10^6\text{yr}$). In contrast to the results of the NSSs shown in Fig.1, the cooling behavior of CSSs are more sensitive to intensity of magnetic field at the middle ages ($\sim 10^2 - 10^6\text{yr}$) although these two kinds of SSs are analogous in the old era. In addition, the electron fraction has here hardly any influence on the cooling at the middle ages unlike the case of NSSs. Collecting above all, we can see the cooling curves of CSSs could be consistent with pulsar data for a wild range of parameters in magnetic field.

More surprisingly, the points where the curves turn down can be lined together as a line in logarithm $T - t$ plane, here the band-like structure is supposed to reflect the uncertainties of q_n . And any other cooling curves (to our knowledge) regardless of star models will be below the line due to high heating effect in CSSs, because the neutrino cooling could almost be switched off and the photon cooling is slow enough. So the line is called limit line, expressed as limit temperature

$$T_{\text{lim}} = 10^{7.75}t^{-1/4}\text{K}. \quad (12)$$

In Fig.2 the recent X-ray data indeed distribute under the limit line, which just confirm the theoretical prediction. Consequently the stars along the limit line are possible candidates for CSSs.

Fig.3 presents the cooling curves of CSSs for $\Delta = 0.1\text{MeV}$ (curve 1), 1MeV (curve 2), 10MeV (curve 3), and 100MeV (curve 4) with $B = 10^9\text{G}$. We see that the cooling curves are independent on the gap at a very large parameter scale ($\Delta \sim 10 - 100\text{MeV}$). Therefore the uncertainties of the value of the gap cannot affect the cooling behavior and the limit line, which are determined by the effect of DH.

6. Summary and conclusion

We here studied the cooling behavior of CSS with a rotating crust. The presence of the CFL strongly suppresses the neutrino emission and the quark specific heat. The DH process and surface emission dominate the cooling of CSS. This leads to extreme difference with the results of NSS and standard neutron star. First, the cooling curves of CSSs with DH are agreement with the pulsar data for a wide range of parameters. Unlike NSS and standard neutron star, cooling curves of CSSs, given an appropriate intensity of magnetic field, can form a plateau to be so long that the stars have higher temperature for a long time and may be observed in the old era. Secondly, the magnetic field play an important role in the cooling history of the stars. The temperature of CSS with strong magnetic field ($B \geq 10^{10}\text{G}$) is higher than standard neutron star while lower for weak field ($B \leq 10^{10}\text{G}$) condition at the middle ages. Thirdly, we find a limit line that can't be made a breakthrough by all theoretical cooling curves involving many model and the data except millisecond pulsars. We think that the stars along the limit line may have the candidates for SSs. Finally, we realize that the cooling behavior of CSS is almost independent of the pairing gap. Thus our conclusions are not influenced by the uncertainties of the gap predicted by color superconducting physics.

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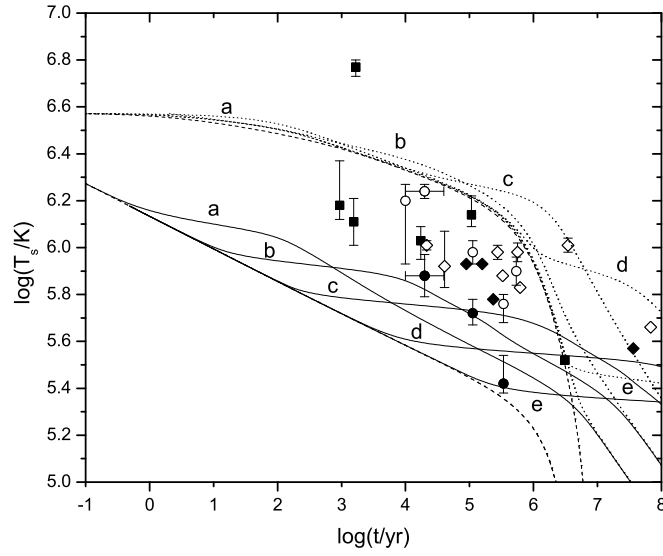


Fig. 1.— Cooling curves of NSSs with $\alpha_c = 0.1$, $Y_e = 10^{-5}$ (solid lines) and $\alpha_c = 0.35$, $Y_e = 0$ (dotted lines) for $B = 10^{12}\text{G}$ (curve a), 10^{11}G (curve b), 10^{10}G (curve c), 10^9G (curve d), 10^8G (curve e), and the curves without deconfinement heating (dashed lines).

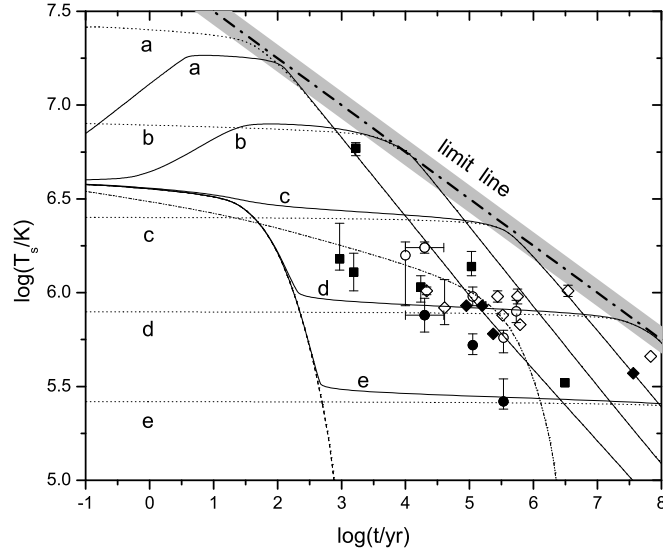


Fig. 2.— Cooling curves of CSSs with $\Delta = 100\text{MeV}$, $\alpha_c = 0.1$, $Y_e = 10^{-5}$ (solid lines) and $\alpha_c = 0.35$, $Y_e = 0$ (dotted lines) for $B = 10^{12}\text{G}$ (curve a), 10^{11}G (curve b), 10^{10}G (curve c), 10^9G (curve d), 10^8G (curve e), and the curve without deconfinement heating (dashed line). Dash-dot-dotted line correspond to standard neutron star and the dash-dotted one to limit line, the band-like structure is supposed to reflect the uncertainties of q_n .

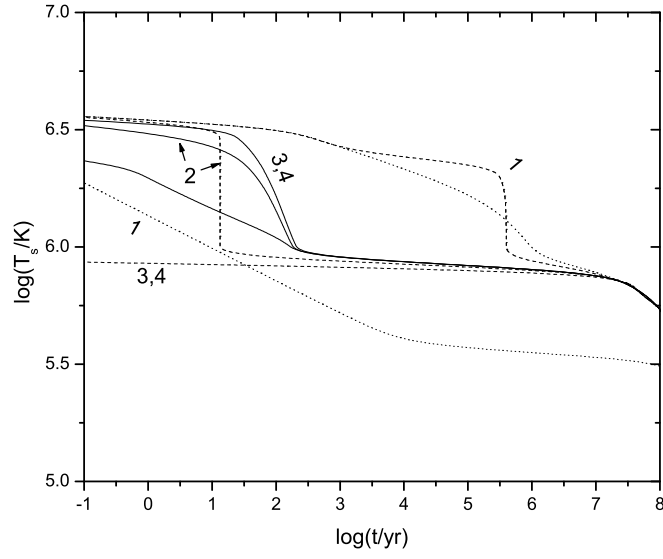


Fig. 3.— Cooling curves of CSSs with $B = 10^9 \text{G}$, $\alpha_c = 0.1$, $Y_e = 10^{-5}$ (solid lines) and $\alpha_c = 0.35$, $Y_e = 0$ (dashed lines) for $\Delta = 0.1 \text{MeV}$ (curve 1), 1MeV (curve 2), 10MeV (curve 3), and 100MeV (curve 4). The dotted lines correspond to NSSs.